# First Measurements of $\psi'$ Production and $J/\psi$ Polarization versus Transverse Momentum in $p+p$ Collisions at $\sqrt{s} = 200$ GeV at Midrapidity in the PHENIX Experiment at RHIC


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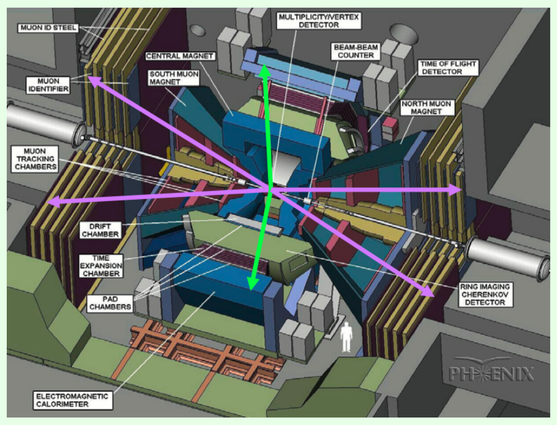
## Introduction

- Charmonia are predominantly generated in hadronic collisions via gluon fusion and their production can be calculated in perturbative QCD, but the details of their hadronizaton process remain unclear;
- Different models of production mechanisms have been proposed to account for non-perturbative contributions;
- Methods to calculate the cross section include:
  - **Non relativistic QCD (NRQCD)**. Effective field theory where the production is a combination of color singlet (CSM) and octet (COM) states. Calculations explained the $J/\psi$ and $\psi'$ direct production cross sections using (COM) at CDF (**PhysRevLett.79.572 (1997),PhysRevLett.79.578 (1997)**), but failed to predict their transverse polarization trend as $p_T$ increases (**PhysRevLett.85.2886**);
  - **Color Evaporation Model (CEM)**. Production is a empirical fraction of $Q\bar{Q}$ heavy quark cross section integrated over 2mc and 2mD (**IntJModPhysA.10.3043 (1995)**). Color octet turns to singlet by soft gluon evaporation.
  - **pQCD with 3-gluon fusion**. Formation done by (gg)8+g fusion. Complete perturbative treatment (**EurPhysJC.39.163171 (2005)**).
  - **CSM with $s$-channel cut Contribution**. Intermediate $c\bar{c}$ interactions are proposed that reproduced the data at low and mid-range transverse momenta $p_T$ from the Fermilab Tevatron and RHIC-BNL. The $J/\psi$ produced in this manner are longitudinally polarized (**PhysRevLett.100.032006 (2008)**).

## PHENIX Detector




**Central Arms**:

- $J/\psi \rightarrow e^+e^-$ , $\psi' \rightarrow e^+e^-$ ;
- $|\eta| < 0.35$;
- $p_e > 0.2$ GeV/c;
- $\Delta\phi = \pi$ (2 arms $\times \pi/2$)

**Forward Rapidity Arms**

- $J/\psi \rightarrow \mu^+\mu^-$;
- $1.2 < |\eta| < 2.2$;
- $p_\mu > 1.0$ GeV/c;
- $\Delta\phi = 2\pi$

**Global Detectors**

- Beam-Beam Counter (BBC);
- Zero Degree Calorimeter (ZDC);
- Reaction Plane Detector (RxNP).

**Integrated Luminosity in $p+p$ Collisions at $\sqrt{s} = 200$ GeV**

- 3 $\times$ more luminosity in Run 6 than in Run 5.

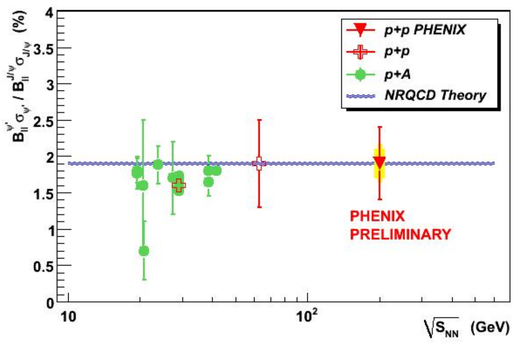
## Invariant Yield Calculation

The invariant cross section of ($\psi$ states) via the $e^+e^-$ decay mode can be extracted experimentally as follows:

$$\frac{B_{ee}}{2\pi p_T}\frac{d^2\sigma_\psi}{dp_T dy} = \frac{1}{2\pi p_T}\frac{n_\psi(p_T)}{\int L dt \epsilon(p_T)\Delta p_T \Delta y} \quad (1)$$

where $B_{ee}$ is the charmonium branching ratio to the di-electron decays (5.94 $\pm$0.06 % for $J/\psi$ and 7.52 $\pm$ 0.17 $\times$ $10^{-3}$ for $\psi'$ , **PhysLettB.667.1 (2008)**), $n_\psi$ is the number of the particular $\psi$ particle, $\epsilon$ is the overall efficiency including geometric acceptance, reconstruction and trigger efficiencies; $\Delta y$ is the rapidity bin width, $\Delta p_T$ is the $p_T$ bin width and $\int Ldt$ is the integrated luminosity.

## Feed-down Contribution to $J/\psi$ Production in Run 6 $p+p$ collisions with PHENIX Central Arms $|\eta| < 0.35$




- About 40-50 % of the quarkonium ground states $J/\psi$ and $\Upsilon$ (1S) produced in hadronic collisions originate from the decay of higher excitations (**PhysRevD.64.094015**). Quarkonium production through feed-down is important because quarkonium states are used to probe the hot and dense medium created in high energy nucleus-nucleus collisions.
- The fraction of $J/\psi$ from the $\psi'$ decay is represented by the ratio $\mathcal{F}_{\psi'}$ which is defined as follows:

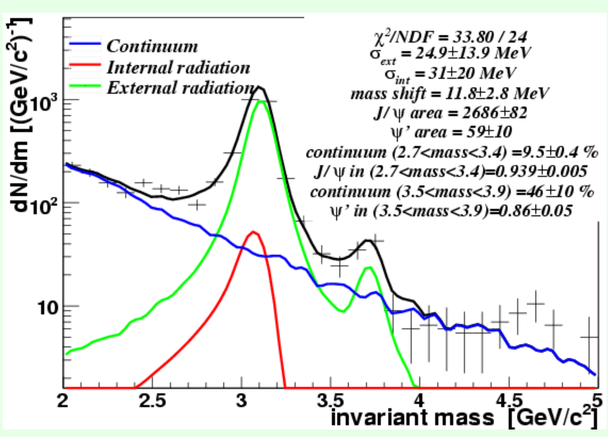
$$\mathcal{F}_{\psi'} = BR(\psi' \rightarrow J/\psi + X)\frac{\sigma_{\psi'}}{\sigma_{J/\psi}}, \quad (2)$$

where $BR(\psi' \rightarrow J/\psi + X) = 0.574 \pm 0.009$ is the branching ratio for the $\psi' \rightarrow J/\psi + X$ mode (**PhysLettB.667.1 (2008)**), $\frac{\sigma_{\psi'}}{\sigma_{J/\psi}}$ is the production cross sections ratio between $\psi'$ and $J/\psi$ .

$\mathcal{F}_{\psi'} = 0.086 \pm 0.025$ (**PHENIX**);

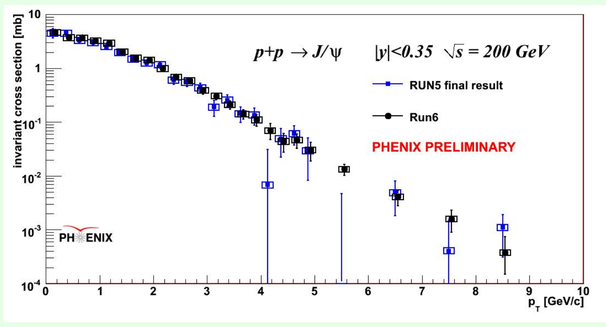
$\mathcal{F}_{\psi'} = 0.08 \pm 0.02$ (**PhysRevD.64.094015**).

## Invariant Mass Spectrum in Run 6 $p+p$ with PHENIX Central Arms $|\eta| < 0.35$



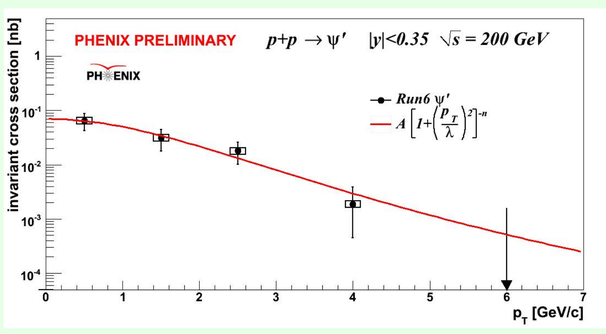

Invariant mass spectrum for dielectron pairs after subtracting the like-sign background. The mass window for the $J/\psi$ is [2.7-3.4] GeV/c$^2$ and for the $\psi'$ is [3.5-3.9] GeV/c$^2$. The mass spectrum was fit with line shapes generated from Monte Carlo simulation of continuum contribution (correlated D and B mesons and Drell-Yan), (**PhysLettB.670.313 (2009)**). The external radiation was reproduced by the PHENIX Integrated Simulation Application code based on the GEANT3 and the internal radiation was derived from the analytical formula described in **hep-ex/0510076** to account for radiative effects in the mass spectrum.

## $J/\psi$ Production in Run6 $p+p$ collisions with PHENIX Central Arms $|\eta| < 0.35$



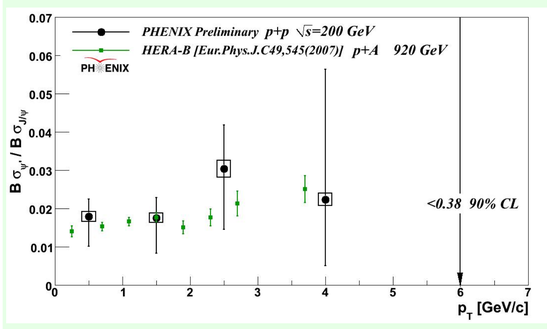

- Brand new yield measurement from larger luminosity in Run6 agrees with published Run 5 $p+p$ results (**PhysRevLett.98.232002 (2007)**)
- $J/\psi$ Total cross section times dielectron branching ratio:
  45.3±1.0(stat)±5.4(syst)±4.5(global) nb
  41.0±0.9(stat)±4.9(syst) nb, $p_T < 7$GeV/c
- average $p_T$ square:
  $\langle p_T^2 \rangle = 4.06 \pm 0.13(\text{uncorr}) \pm 0.11(\text{corr})$. $p_T < 5$GeV /c;
  $\langle p_T^2 \rangle = 4.48 \pm 0.14(\text{uncorr}) \pm 0.12(\text{corr})$, $p_T < 7$GeV /c;
  $\langle p_T^2 \rangle = 4.60 \pm 0.15(\text{uncorr}) \pm 0.11(\text{corr})$.

## $\psi'$ Production in Run 6 $p+p$ collisions with PHENIX Central Arms $|\eta| < 0.35$




- **First $\psi'$ production versus transverse momentum measurement at RHIC!**
- $\psi'$ Total cross section times dielectron branching ratio:
  $0.88^{+0.30}_{-0.20}$(stat)±0.12(syst) nb,
  $p_T < 7$GeV/c;
- average $p_T$ square:
  $\langle p_T^2 \rangle = 4.56\ ^{+1.46}_{-1.15}$ (uncorr)± 0.13(corr), $p_T < 5$GeV /c;
  $\langle p_T^2 \rangle = 7.13\ ^{+2.0}_{-2.6}$ (uncorr) ± 0.26(corr), $p_T < 7$GeV /c.

## $\psi'$ to $J/\psi$ cross sections ratio measurement in Run 6 $p+p$ collisions with PHENIX Central Arms $|\eta| < 0.35$

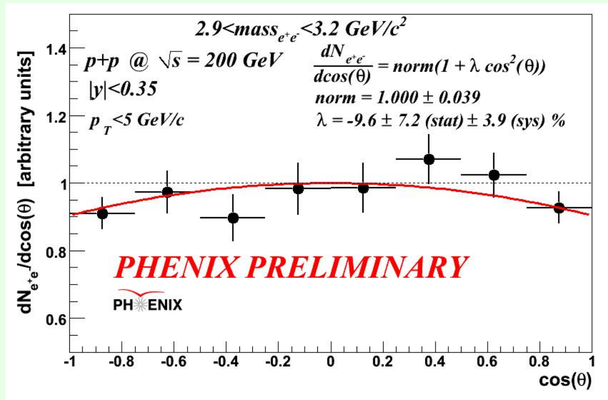


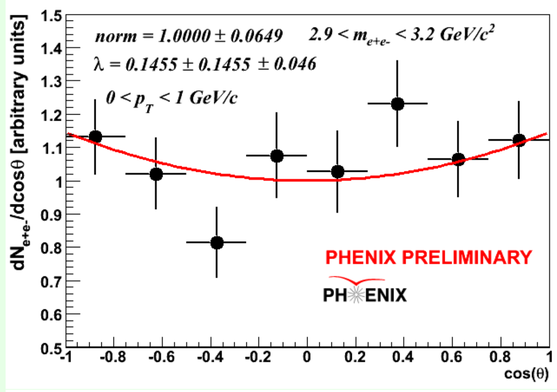

- The ratio $\mathcal{R}_{\psi'}$ for $\psi'$ to $J/\psi$ is defined:

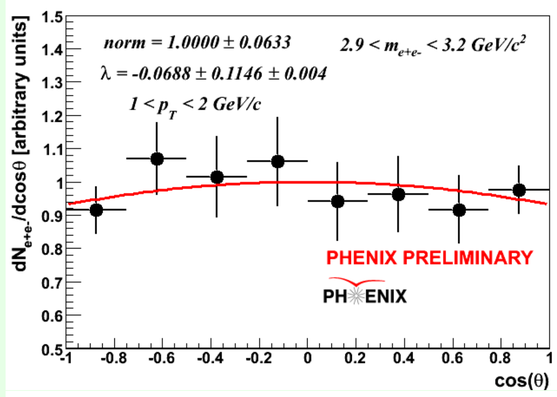
$$\mathcal{R}_{\psi'} = \frac{BR(\psi' \rightarrow e^+e^-)}{BR(J/\psi \rightarrow e^+e^-)}\frac{\sigma_{\psi'}}{\sigma_{J/\psi}},$$

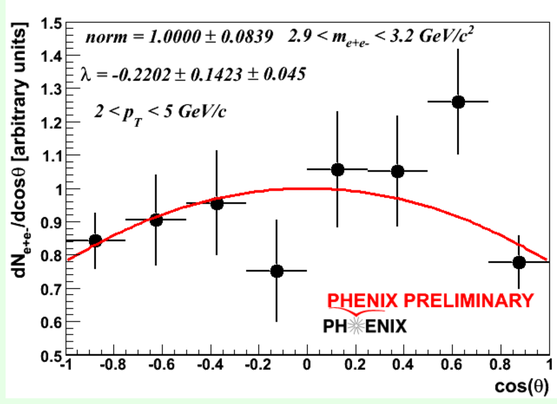
  where $BR(\psi' \rightarrow e^+e^- = (7.52 \pm 0.17) \times 10^{-3}$ and $BR(J/\psi \rightarrow e^+e^-) = (5.94 \pm 0.06\%)$ **PhysLettB.667.1 (2008)**.
  $\mathcal{R}_{\psi'} = 0.019 \pm 0.005(\text{stat}) \pm 0.002$ (sys) (**PHENIX**).
- Good agreement with HERA-B fixed target experiment.

## $J/\psi$ Polarization in Run 6 $p+p$ collisions with PHENIX Central Arms $|\eta| < 0.35$




$$dN/dcos(\theta) = A[1 + \lambda \cos^2\theta], \quad (4)$$

$\theta$ is the angle between the positive lepton momentum direction and the $J/\psi$ momentum direction in its rest frame.
$\lambda > 0$ transverse polarization;
$\lambda < 0$ longitudinal polarization.

- NRQCD predicts:
  - transverse for octet states with $p_T >> M_{J/\psi}$ ;
  - longitudinal for singlet states with $p_T >> M_{J/\psi}$ .
- CEM expects no polarization;
- 3-gluon fusion expects transverse polarization for low $p_T$ and longitudinal for $p_T >> M_{J/\psi}$ (**Eur. Phys.J. C39163**);
- there is a very small chance that the polarization for the highest $p_T$ point is zero or transverse in agreement with recent CSM with $s$-channel cut contribution prediction (**PhysRevLett.100.032006**);
- small polarization at mid-rapidity seems consistent with $s$-channel cut theory (**PhysRevLett.100.032006**) but polarization observed at forward rapidity is smaller than model prediction.